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Real-Time Instrumentation for Mass Loss Measurements on Laser Materials

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Technical Report

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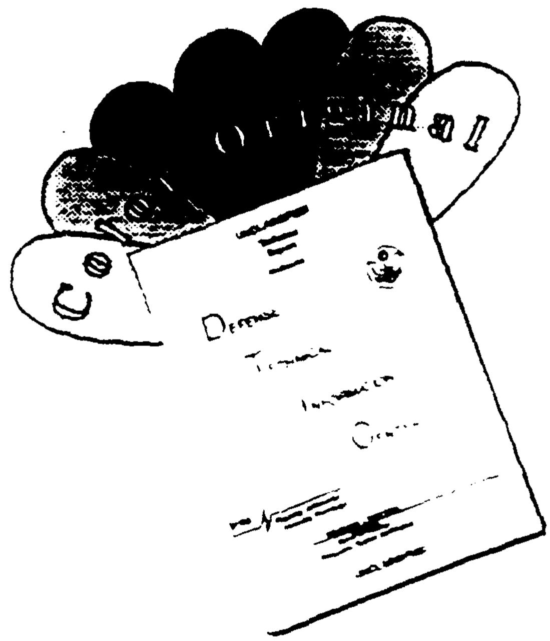

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13. ABSTRACT *(Maximum 200 words)*

Real-Time mass loss instrumentation has been developed for the Defense Nuclear Agency to provide a means of studying laser and target interaction during target illumination by continuous wave (CW) high energy lasers. Mass loss measurements that were addressed in this program are the transients that occur during and immediately following coupon illumination. The high frequency inertial mass measurement technique furnishes rapid mass measurements required to resolve mass transients. The instrumentation possesses resistance to impulsive forces present during material ablation allowing continuous measurements during an event. Tests performed using the prototype balance and a 50 kW CW laser demonstrated this concept to be valid. Present mass resolution is +/–600 micrograms at a time resolution of 500 microseconds. There do not appear to be any technological barriers that would prevent significant time and mass resolution improvements.

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Conversion factors for U.S. Customary to metric (SI) units of measure.

MULTIPLY	BY	TO GET
pound	0.0022	gram
inch	0.3937	cm
inch*pound/second	0.1130	watt
Btu	1.0551×10^3	joule
cycles/second	1	Hz

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SECTION 1

INTRODUCTION

1.1 PROGRAM OVERVIEW.

Development of Real-time mass loss instrumentation (herein called the balance) for the Defense Nuclear Agency (DNA) was motivated by the need to study the target/laser interaction during target illumination by high energy lasers (HEL's). Mass loss measurements addressed in this program include the transients that occur during and immediately following coupon illumination by a continuous wave (CW) laser in environments ranging from vacuum to atmospheric.

Mass and time resolution were the goals of this program. There values were determined to resolve transients which occur during and just following laser illumination. Mass loss transients include the following conditions:

1. Reductions in mass loss rate at the initial target illumination as a result of both initial heating as well as coating burn off.
2. Plasma interference.
3. Beam blockage from ablated material.
4. Continued mass loss following the termination of target illumination.

The balance would also be used in studying the effects of varying laser parameters and aid in the development of HEL's.

1.2 DESIGN GOALS.

The balance developed in this contract should be capable of measuring total mass loss, mass loss transients and total momentum transferred. Mass and time resolution requirements were obtained from the need to perform the following range of tests. The laser power dissipated can be in the range of 6.25 kW to 100 kW with test durations from 10 ms to 160 ms. The balance should be capable of testing materials with a Q* of 5 kJ/gram to 30 kJ/gram. Coupons should be capable of accommodating laser spot sizes ranging from 1 cm^2 to 20 cm^2. The time resolution goal is 100 microseconds. The mass resolution goal is 10% of the mass loss per time resolution window or 2 micrograms maximum resolution.

Since the proposed project was only given 1/2 the funding required to produce a complete deliverable instrument, a proof of concept instrument became the goal of this program. Elements of the design that have been previously well proven and were not thought to greatly influence the results were omitted. One example is temperature control. Because of the short test durations temperature effects were assumed to be minimal. Compromises were made based on practical limits of component materials and sizes. For example, a 100 microsecond balance would require a balance frequency to be 30 times greater than any previous Rupprecht & Patashnick, Co. (R&P) balance. Instead an intermediate design was selected having the following design goals. The time resolution goal is 250 microseconds with a mass resolution of 20 micrograms per time resolution window.

SECTION 2

BACKGROUND

2.1 INERTIAL MASS MEASUREMENT.

Inertial mass measurement is achieved by oscillating a mechanical system at resonance and monitoring the frequency of the system as its mass is altered. The resonant frequency (f) of the oscillating system can be described by

$$f^2 = \frac{K_0}{M_0} \qquad (2.1)$$

where K_0 is related to the spring constant and M_0 is the effective oscillating mass. When a mass change Δm occurs, such as the ablation of a coupon by laser illumination, the frequency shifts. This frequency shift Δf is related to the mass change Δm by the expression:

$$\Delta m = 2 \times M_0 \times \frac{\Delta f}{f} \qquad (2.2)$$

The effective oscillating mass M_0 consists of the coupon, coupon holder and a portion of the balance structure which is flexing. Changes in M_0 cause frequency changes. It is important for the entire coupon to translate through the total amplitude of oscillation. Any deflection of the coupon will alter the frequency without a mass change. Therefore, the coupon holder must provide a very rigid support for the coupon during the entire test. Equation 2.2 clearly shows that minimizing M_0 will increase the mass resolution.

2.2 LINEAR MOTION MICROBALANCE.

A R&P patented balance system called the linear motion balance comprised of welded crossed tubing oscillating in a linear motion has definite advantages over previous inertial balances utilizing a cantilever beam or pendulum type elements. The most important is that the linear motion eliminates the positional dependencies of the former designs. Therefore, crater size, shape and position on the coupon will not effect the measurement of mass. Another benefit to the linear motion balance is its symmetric design which suppresses torsional modes of operation resulting from nonsymmetric coupon mounting and ablation. A third very important advantage is that the welded cross design permits relatively high energy storage which helps to suppress the impulsive forces present during coupon ablation.

The linear motion balance permitted a high frequency design, required for short time resolution, that would have been difficult to accomplish with either the cantilever beam or pendulum type balance.

Figure 2-1 shows a detailed conceptual drawing of a complete balance system. A sensor unit, electronics unit and a personnel computer make up the 3 main components of the system. Components relating to temperature control, purge air, enclosure and momentum calculation elements were not present at the verification test.

2.3 MASS MEASUREMENTS.

The balance operates as a harmonic oscillator (Paragraph 2.1). Driving the balance at resonance is accomplished by utilizing a feedback loop consisting of a velocity sensor, amplifier, automatic gain control (AGC) and mechanical driver. The velocity sensor converts the relative velocity difference between the coupon and the linear balance structure to a voltage signal which is first filtered and then maintained constant with the AGC circuit and amplifier. The signal is then used to drive the mechanical driver. The system is now being driven at its resonant frequency. Any frequency change will represent a mass change of the oscillating coupon. As the coupon is ablated the resonant frequency changes in proportion to the mass loss. A sampling of the velocity signal provides a record of the balance frequency which will be processed to yield mass loss.

Sampling of the filtered velocity signal is at a rate of 1 MHz. Frequency is obtained from this signal by digitally filtering the data and then performing a curve fit to data. An RMS error minimization technique is used to determine the coefficients of the following equation.

$$y=(A\times\sin(B\times t+D))+C \tag{2.3}$$

The following four coefficients are determined during the curve fit procedure:

A = Peak amplitude
B = Frequency of oscillation
C = DC Voltage offset
D = Phase angle

Only the value for frequency is required for mass calculations. However, the other coefficients were utilized as diagnostic tools. The curve fit procedure was applied to windows of data equal in length to 1 balance period. Subsequent windows are shifted 1/2 period yielding a time resolution of 250 microseconds for a balance frequency of 2000 Hz.

The vibrational mode reinforced by the driven system is one that yields maximum coupon amplitude relative to the linear balance structure. This high amplitude of oscillation stores maximum energy in the elastic elements minimizing disruption from outside forces. The maximization of force supplied by the driver will also minimize impulse noise on the velocity signal. Forces such as the impulses present during material ablation are reduced to high frequency low amplitude noise on the sampled signal which can be easily removed through digital filtering.

SECTION 3

BALANCE CALIBRATION

Balance calibration is the process of determining the spring constant, K_0, of the balance. Because the welded element design behaves like a fixed end beam the linear motion balance spring constant is a function of balance oscillation amplitude. Therefore, for each amplitude in which the balance is operated a calibration is required.

As discussed previously, the velocity of the coupon is maintained constant allowing the amplitude of oscillation to vary as the oscillating mass changes. Therefore, the spring constant changes slightly as the coupon is ablated and a curve defining K_0 is required. This calibration can be easily made with a set of calibration masses. Previous R&P inertial balances have successfully used this technique of calibration.

Because of insufficient time to perform a comprehensive calibration a single value K_0 was used for the results contained within resulting in a maximum error of 3%.

SECTION 4

LASER VERIFICATION TEST

Verification testing was performed to determine the performance capabilities of the mass loss instrumentation. Laser parameters were varied to provide test conditions that would demonstrate resolution of the instrumentation. Table 4-1 describes the laser tests performed on the Electric Discharge Coaxial Laser (EDCLII) at Phillips Laboratory's Laser Effects Test Facility (LETF) located at Kirtland Air Force Base in New Mexico. A schematic representation of the layout of the test setup is shown in Figure 4-1.

4.1 TEST DESCRIPTION.

Time constraints and laser availability caused it to be not feasible to test all of the operating configurations. Because of the time required to obtain a vacuum, ambient air was selected over vacuum to maximize the number of tests that could be performed. A single spot size was maintained due to the fairly long time required to modify the optics. Parameters that were easily modified and demonstrate the balances mass resolution were laser power and illumination duration.

4.2 COUPON MOUNTING.

As discussed previously the primary concern of mounting any target is to ensure that the entire coupon oscillates as a rigid body. This was accomplished by mounting the 0.635 cm thick, 1.27 cm square coupon to an aluminum target holder of the same dimensions. The coupon was bonded to the coupon holder with epoxy. The target holder was tapped and a set screw was used to make the balance interface.

Secure mounting of the coupon assembly to the balance was verified by tightening the coupon until there was no change in the AGC voltage.

4.3 TEST PROCEDURE.

The following test procedure was followed:

Weigh coupon / coupon holder assembly on a gravitational balance to obtain an initial weight.
Arm data acquisition software .
Turn on the balance and verify integrity of coupon attachment.
Power up the laser.
Initiate sequencer when laser power is stable. The sequencer will provide the following triggers:

- Start slow shutter
- Start camera equipment.
- Start data acquisition software.
- Start fast shutter.
- End fast shutter.
- End camera equipment.
- End slow shutter.
- End data acquisition software.

Obtain laser power readings.
Shut down laser.
Shut down balance.
Weigh coupon / coupon holder assembly on a gravitational balance to obtain a final weight.

4.4 DISCUSSION OF TEST PARAMETERS.

4.4.1 Balance Parameters.

For most tests the balance drive current was maintained at approximately 2.0 amps which was determined to yield maximum coupon amplitude with maximum mass resolution. The AGC voltage was monitored to provide feedback on the integrity of the coupon attachment to the balance. One set of tests was performed with the drive current increased to 3.0 amps so that a balance amplitude comparison could be made.

4.4.2 Laser parameters.

The laser power shown in Table 4-1 is the power at the laser output, prior to being reduced by mirrors and windows. The actual power is the laser power reduced by the 14% lost in the beam train. The illumination duration is estimated from the fast shutter P/T curve which represents relative shutter power.

The actual energy shown in Table 4-1 is calculated from the actual power and illumination duration.

Table 4-1. Laser test summary.

Test no.	Coupon no.	Balance parameters		Laser parameters				Mass statistics				
		Drive current (amps)	AGC voltage (volts)	Laser power (kW)	Actual power (kW)	Illumination duration (seconds)	Actual energy (kJ)	Mass before (grams)	Mass after (grams)	Total mass loss (grams)	Average mass loss (μ grams)	Average Q* (kJ/gram)
1	LT4	2.028	0.170	44.50	38.27	0.070	2.68	4.4280	4.2129	0.2151	768	12.454
2	LT5	2.050	0.170	44.15	37.97	0.045	1.71	4.4666	4.3249	0.1417	787	12.058
3	LT6	2.050	0.180	28.22	24.27	0.040	0.971	4.4637	4.3774	0.0863	539	11.249
4	LT7	2.050	0.180	18.90	16.25	0.040	0.65	4.4106	4.3570	0.0536	335	12.127
5	LT8	2.050	0.184	18.79	16.16	0.040	0.65	4.4005	4.3517	0.0488	305	13.320
6	LT9	2.080	0.187	15.94	13.71	0.043	0.59	4.4155	4.3694	0.0461	268	12.798
7	LT10	2.080	0.180			0.520		4.4702				
8	LT11	2.080	0.180	15.27	13.13	0.045	0.59	4.4642	4.4152	0.0490	272	12.058
9	LT12	2.080	0.180	10.32	8.88	0.040	0.36	4.3884	4.3610	0.0274	171	13.139
10	LT13	2.080	0.185	9.96	8.57	0.053	0.45	4.4603	4.4257	0.0346	163	13.127
11	LT14	2.080	0.185	10.06	8.65	0.055	0.48	4.4171	4.3754	0.0417	190	11.511
12	LT15	2.080	0.185	9.98	8.58	0.065	0.56	4.4578	4.4129	0.0449	173	12.472
13	LT16	3.11	0.320	9.72	8.36	0.060	0.50	4.4457	4.3982	0.0475	198	10.526
14	LT17	3.170	0.327	10.32	8.88	0.0515	0.46	4.4486	4.4010	0.0476	231	9.608
15	LT18	2.080	0.187	4.94	4.25	0.080	0.34	4.4343	4.4078	0.0265	82.8	12.830

SECTION 5

TEST RESULTS

Tests were performed beginning with the high power short duration tests which removed the largest amounts of mass at the shortest intervals requiring minimum mass resolution. Subsequent tests were performed at reduced power. Illumination durations were increased on some low power tests. One set of tests was performed with the balance driver power increased from 2.0 amps to 3.0 amps.

5.1 FALSE TRIGGER.

The analog signal supplied to the A/D board responsible for initiating data translation may have had noise spikes on it caused by the EMI present in the laboratory during laser power up. In some tests this caused a premature triggering of the data acquisition and the 4 second acquisition time expired prior to the laser event. In other tests, the event took place later in the 4 second data acquisition window. Therefore, the times at which the data was acquired do not correspond to the times supplied by the laser peripherals. Laser test numbers 2, 4 and 8 all had false triggers causing the event to be missed entirely.

5.2 FAST SHUTTER.

Laser illumination durations were obtained from curves representing the fast shutter power. The curve is a square wave representing the duration of the pulse. The rising edge of the pulse is very square and provides a good starting point. However, the falling edge is a decaying curve and makes it difficult to determine exactly when the shutter closed terminating coupon illumination. The shutter is assumed to close when the falling edge is vertical and residual power created most of the decay. Figure 5-1 shows the shutter response during test 3.

Opening and closing of the fast shutter will require a finite amount of time causing the coupon to be partially illuminated. A portion of the change in mass loss rate at the beginning and end of the illumination period can be explained by partial illumination.

The actuation of the fast shutter caused a severe shock to be transmitted from the shutter to the laboratory floor. Isolation between this shock impulse and the balance consisted only of the rubber feet on the balance frame. Data taken to determine the effects of EMI on the ability to measure mass could be used to determine if the frequency disruption seen at the beginning and end of each test is due to electrical or mechanical noise of the shutter actuation. This data was not evaluated due to a lack of time.

5.3 LASER TESTS.

Due to a lack of time no attempt was made to locate events in laser tests 10, 11, 13 and 15. Events were found in laser tests 5, 9 and 12, but were not processed because of time constraints.

5.3.1 Laser Test #1.

Laser test #1 ablated 0.2151 grams in about 0.070 seconds. This test was designed for a material having a Q* of 18 Kj/gram not 12 Kj/gram as the silicon phenolic does. Therefore, the high power pulse ablated through the coupon and into the aluminum. This occurrence although not planned might have shown interesting results as the mass ablation rate changed significantly when the burn material switched from silicon phenolic to aluminum. However, as this occurred the mounting of the coupon loosened fouling the results. Results from test #1 are not offered in this report.

5.3.2 Laser Test #3.

Laser test #3 removed 0.0863 grams of coupon material in about 0.040 seconds. The average power dissipated was 24.27 Kw at the coupon. This data set provided the largest mass loss per unit time, approximately 540 micrograms every 250 microseconds on average making this data set the easiest to resolve.

A curve fit to the data yielded a mass resolution of approximately +/- 600 micrograms at a time resolution of 250 microseconds, slightly higher than the average mass removal for the same time interval. Although, mass removal was not constant and there were most likely periods of mass removal that exceeded the resolution, further discussion will be based on 500 microsecond intervals providing larger average mass loss per interval than balance mass resolution. Increasing the mass resolution period by averaging two shorter periods increases the balance mass resolution approximately 84 micrograms per 1000 microseconds as shown in Figure 5-2. The effect of averaging to obtain a mass calculation every 250 microseconds is an increase in mass resolution of about 20 micrograms. Mass will still be reported at 250 microsecond intervals because it is being calculated as a running average. A disadvantage of reducing the time resolution is a smoothing of transients and sharp changes in mass loss.

Overall mass loss was verified with the before and after coupon weighings on a gravitational balance. There is a 2% difference in between the inertial mass measurement and the gravitational measurement which can be attributed to the simplified balance calibration. See Figure 5-3.

Figure 5-4 shows that the average mass loss rate during illumination is approximately 2 grams per second. Assuming constant power during the event, an average Q* of 11.2 kJ/gram results. As a mass loss verification, the area under the rate of mass loss curve is equal to the total mass loss during the event.

Because of the false trigger discussed above, it is impossible to know exactly when the laser illumination began and ended. Figure 5-4 provides one possibility. An estimate of where the illumination began and ended is based on the change in the rate of mass loss at the end, detailed in Figure 5-5. The mass loss rate decreases from 2.4 grams/second to 1.0 grams/second 40 ms after in initial illumination. The decrease in the rate of mass loss is thought to be the fast shutter closing and the continued burn directly following illumination. It was observed on the video that the plume took some time to disappear. Snapshots of this affect are shown in Figure 5-6.

The fast shutter was probably the cause of the disruption, detailed in figure 5-7, just prior to the sharp increase in mass loss rate. Two possible causes might be electrical noise resulting from the initial trigger or mechanical vibrations of the shutter actuation. In either case, the disruption is only temporary with mass measurements directly following it unaffected. As with any disruption caused by mechanical or electrical interference no permanent mass shifts will result.

5.3.3 Laser Test #6.

During laser test #6, 0.0461 grams was ablated in 0.0429 seconds. The average laser power was 13.71 Kw at the coupon. This data set provided an average mass loss of 268 grams per 250 microseconds resulting in a tighter mass resolution requirement than test #3.

Again, the total mass loss was verified with before and after coupon weighings on a gravitational balance yielding an difference of only .53 mg or 1.1%.

Curve fitting the data resulted in a mass resolution equal to +/- 600 micrograms confirming the resolution of test #3. Averaging was used to increase the mass resolution and decrease the time resolution to 500 microseconds increasing the amount of mass removed per time resolution window.

Figure 5-8 shows that the average mass loss rate during illumination is approximately 1 gram per second. Assuming a constant power of 13.71 kW, the average Q^* is 12.8 kJ/gram.

5.3.4 Laser Test #7.

A test setup error caused the fast shutter to remain open resulting in target illumination for more than 0.5 seconds. The extended illumination duration burned through the coupon and coupon holder separating them completely from the balance. As discussed previously when the coupon is not held perfectly rigid on the balance the mass calculation is in error. Therefore, this test was not considered when evaluating the results.

5.3.5 Laser Test #14.

Laser test #14 removed 0.0476 grams of coupon material in 0.0515 ms. The average power dissipated was 8.88 kW at the coupon.

The balance was operated with the drive current at 3.0 amps which provides a higher coupon oscillation amplitude than previous tests. Higher baseline noise is present with drive currents greater than 2.0 amps because of internal signal interference. This increase can be demonstrated by comparing the baseline prior to the event for this test and laser test #3. The baseline mass resolution for this test is +/-1000 micrograms compared to +/- 600 micrograms for laser test #3. The benefit to operating at a higher amplitude is the increased noise suppression capabilities. However, impulsive noise was not a major factor and increased mass resolution obtained by operating at 2.0 amps or lower is recommended. In order to increase the mass loss per time resolution window the averaging time was increased to 1000 microseconds.

A 1.09 mg or 2.2% difference between the inertial measurement and the gravitational measurement exists. A K_0 that accounts for the balance amplitude will decrease this difference.

Figure 5-9 shows that the average mass loss rate during illumination is approximately 0.9 grams per second which relates to a Q* of 9.6 kJ/gram with a constant power of 8.88 kW. Figure 5-10 shows the post illumination transient and Figure 5-11 shows the duration of illumination.

SECTION 6

CONCLUSION

A large array of data was successfully acquired during the coupon ablation tests. Only a partial analysis of the data collected was possible due to time constraints. The data that was reduced proved that the inertial mass measurement concept for measuring mass loss during a continuous wave laser event is valid and has the potential of meeting all the goals of this program. Mass measurements can be made at the submillisecond rates required to resolve transients during and after ablation. There do not appear to be any technological barriers exist that will impede further mass resolution improvements. Quantifying these transients will be valuable to the laser/material development field.

Mass resolution is presently +/- 600 micrograms in a time resolution of 250 microseconds. These results demonstrate the validity of the measurements and confirm the soundness of the concept.

During development a number of improvements were identified that if implemented could significantly improve mass resolution. They include swapping the existing switching power supplies with linear supplies, and thereby reducing high frequency noise present on the velocity signal. Providing improved shielding between the mechanical driver and the velocity sensor would reduce interference that limits the amplitude of oscillation and reduces the mass resolution. Improved shielding will provide better isolation from emitted electrical noise from nearby equipment. Adding temperature control would ensure stability for longer duration tests. Improving the balance suspension would provide better isolation from structureborne noise. Modifying the trigger from an analog signal to a software trigger would prevent false triggers.

One important observation is that the signal noise did not increase due to the impulsive forces present during ablation. This may permit balance operation at lower amplitudes providing an even quieter signal. Another benefit to lower amplitudes is that the spring constant of the balance behaves more linearly allowing for an easier calibration.

Figures 5-5 and 5-10 show the post illumination reduction in mass loss rate for tests #3 and #14, respectively. The reduction in the mass ablation rate was observed in all tests. As averaging times become longer the change is less apparent than in the 250 microsecond data. It is confirmed by the photographs in Figure 5-6 which shows that following illumination the plume is still present although decreasing in size. This change in the rate of mass loss is significant because it shows the balance is capable of measuring the transients of interest to the laser community.

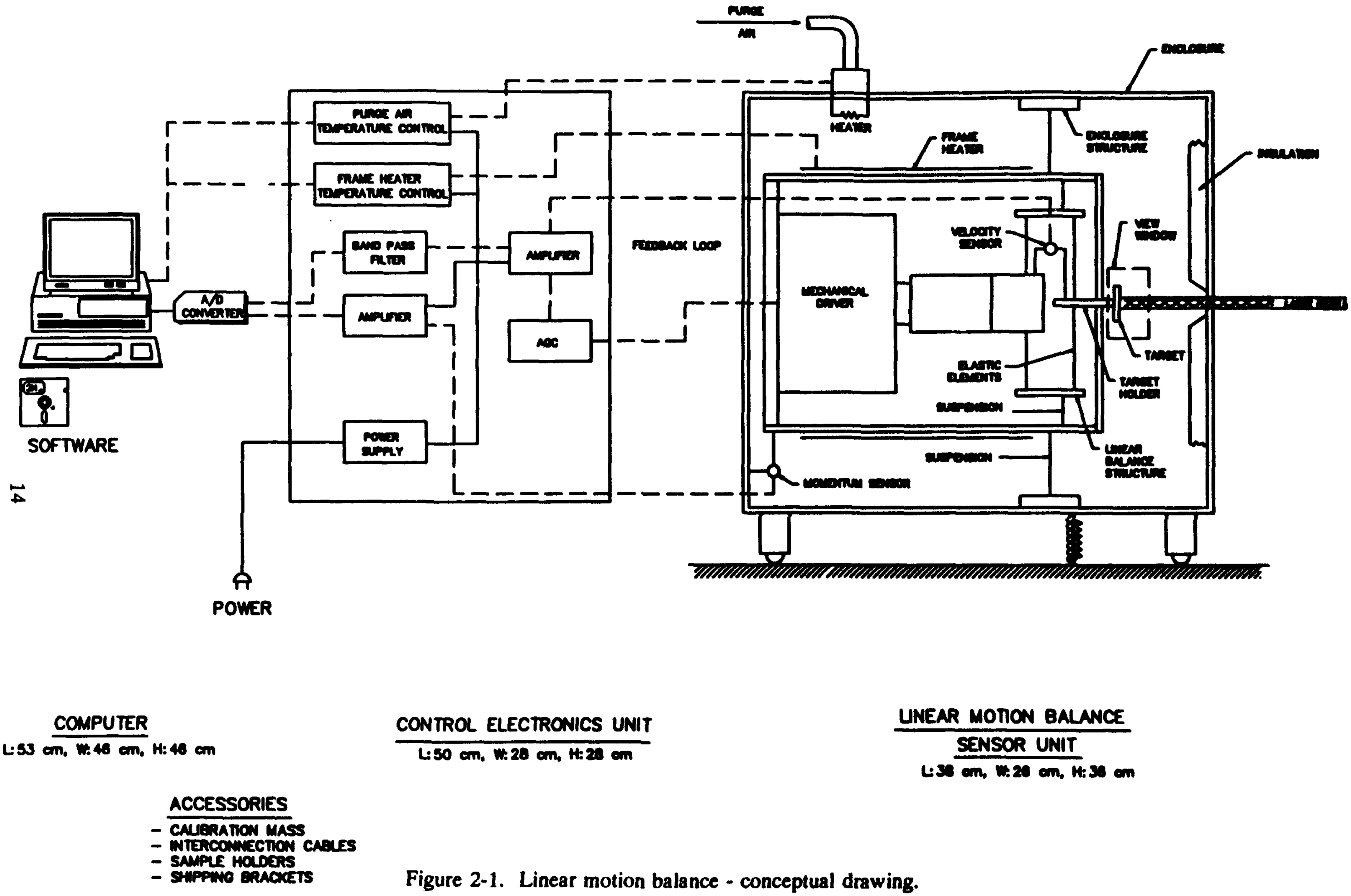
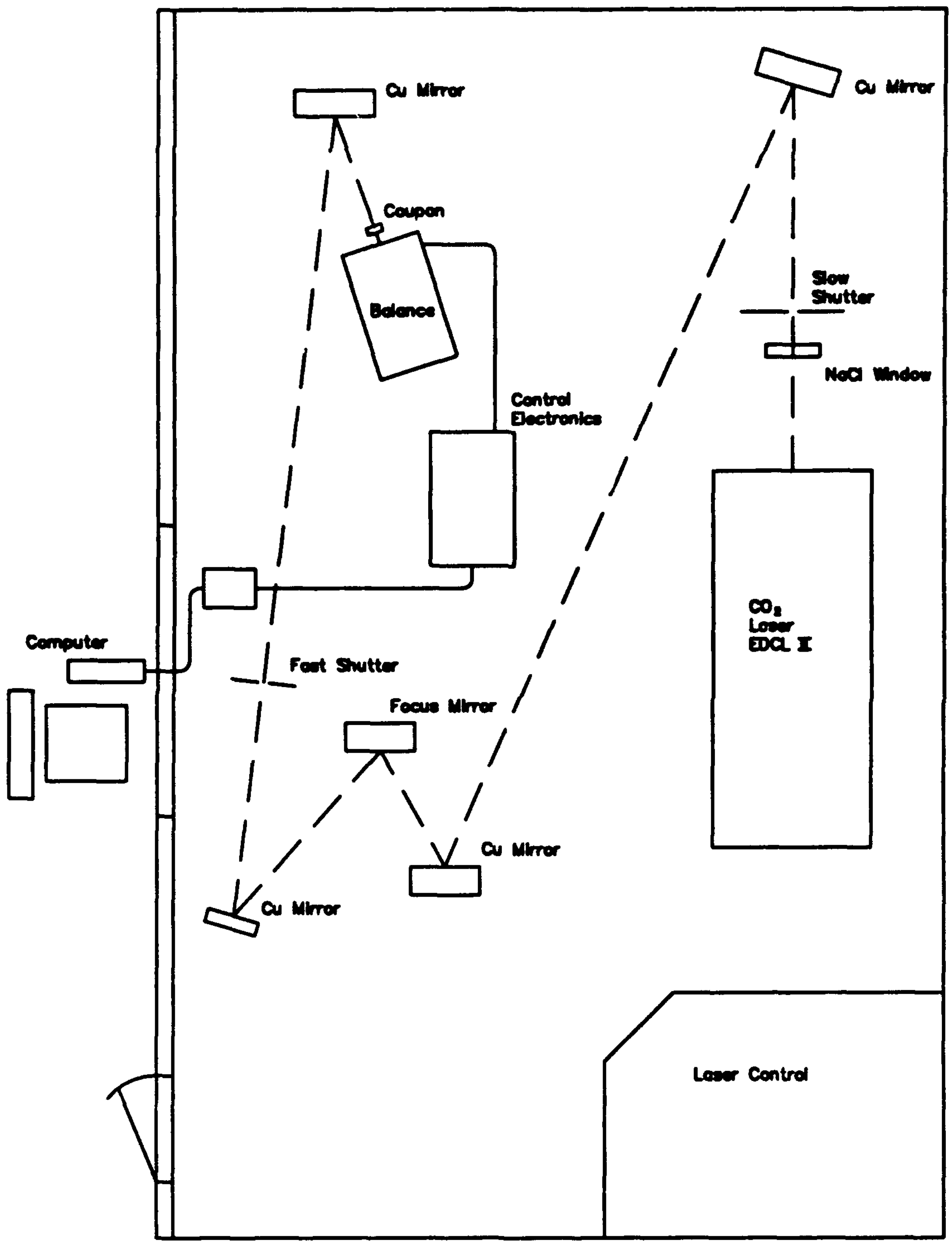


Figure 2-1. Linear motion balance - conceptual drawing.



Electric Discharge Coaxial Laser II
Phillips Laboratory
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Figure 4-1. Test setup - coupon ablation test.

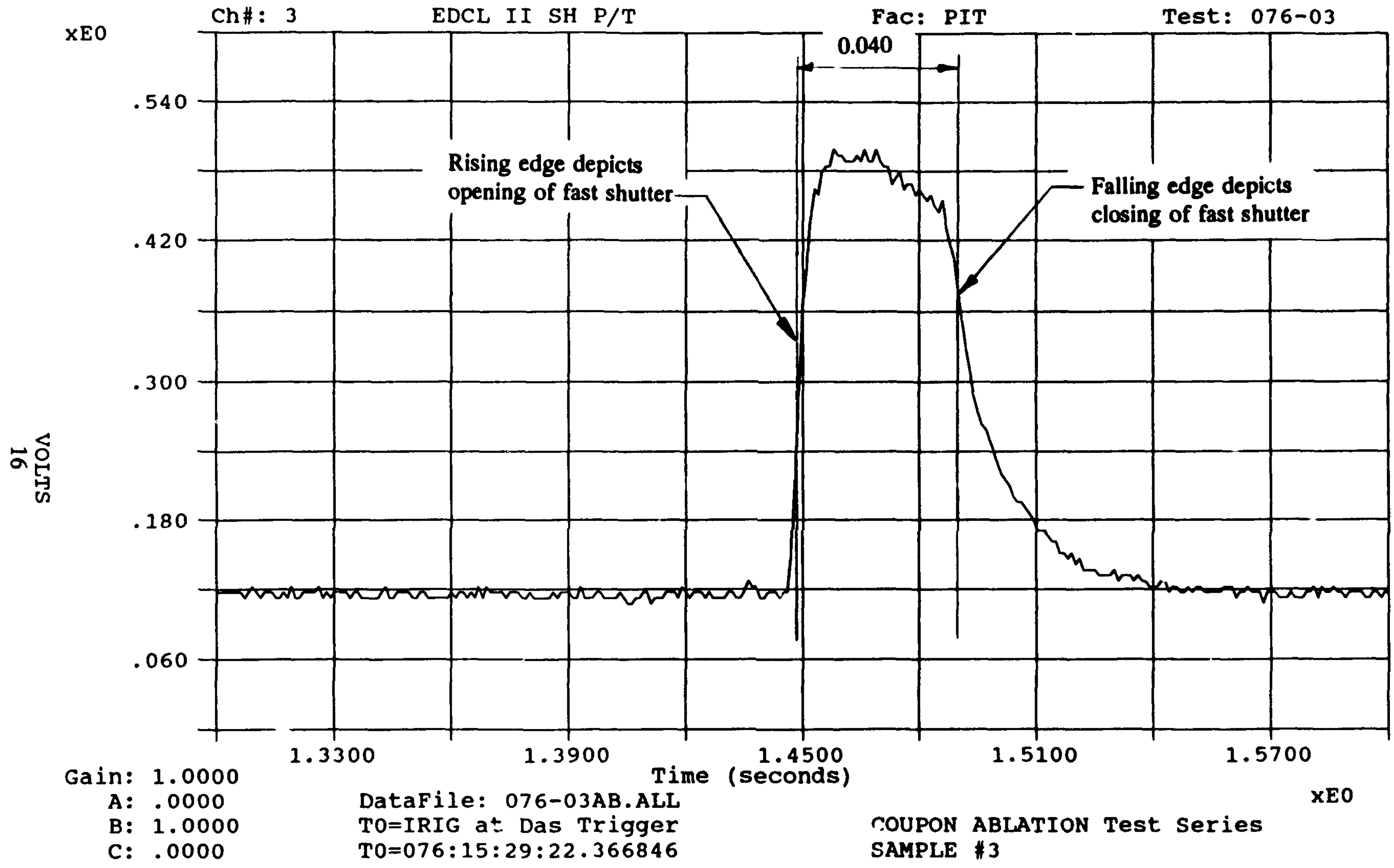


Figure 5-1. Coupon ablation test #3 - fast shutter response.

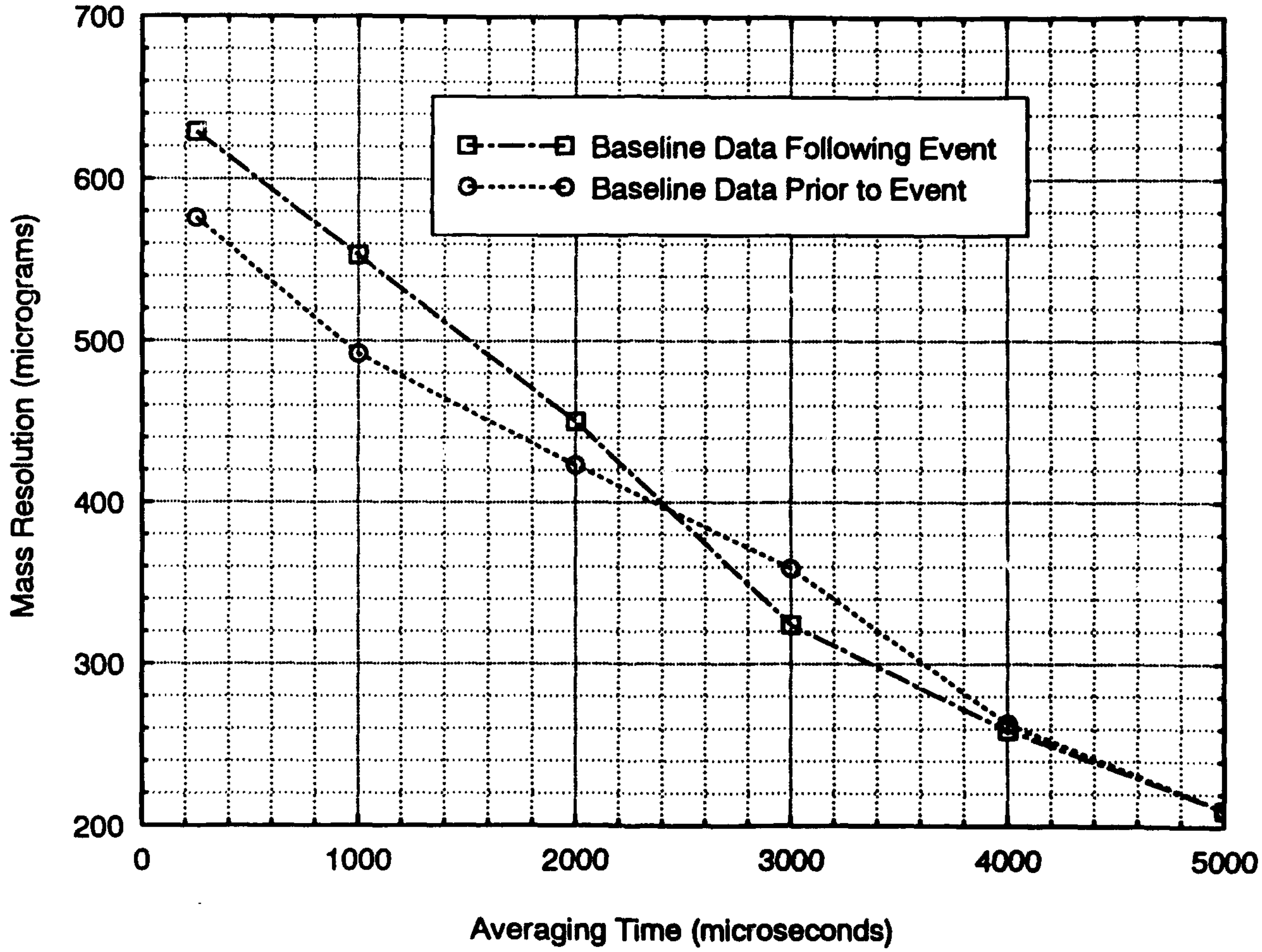


Figure 5-2. Coupon ablation test #3 – mass resolution vs time resolution.

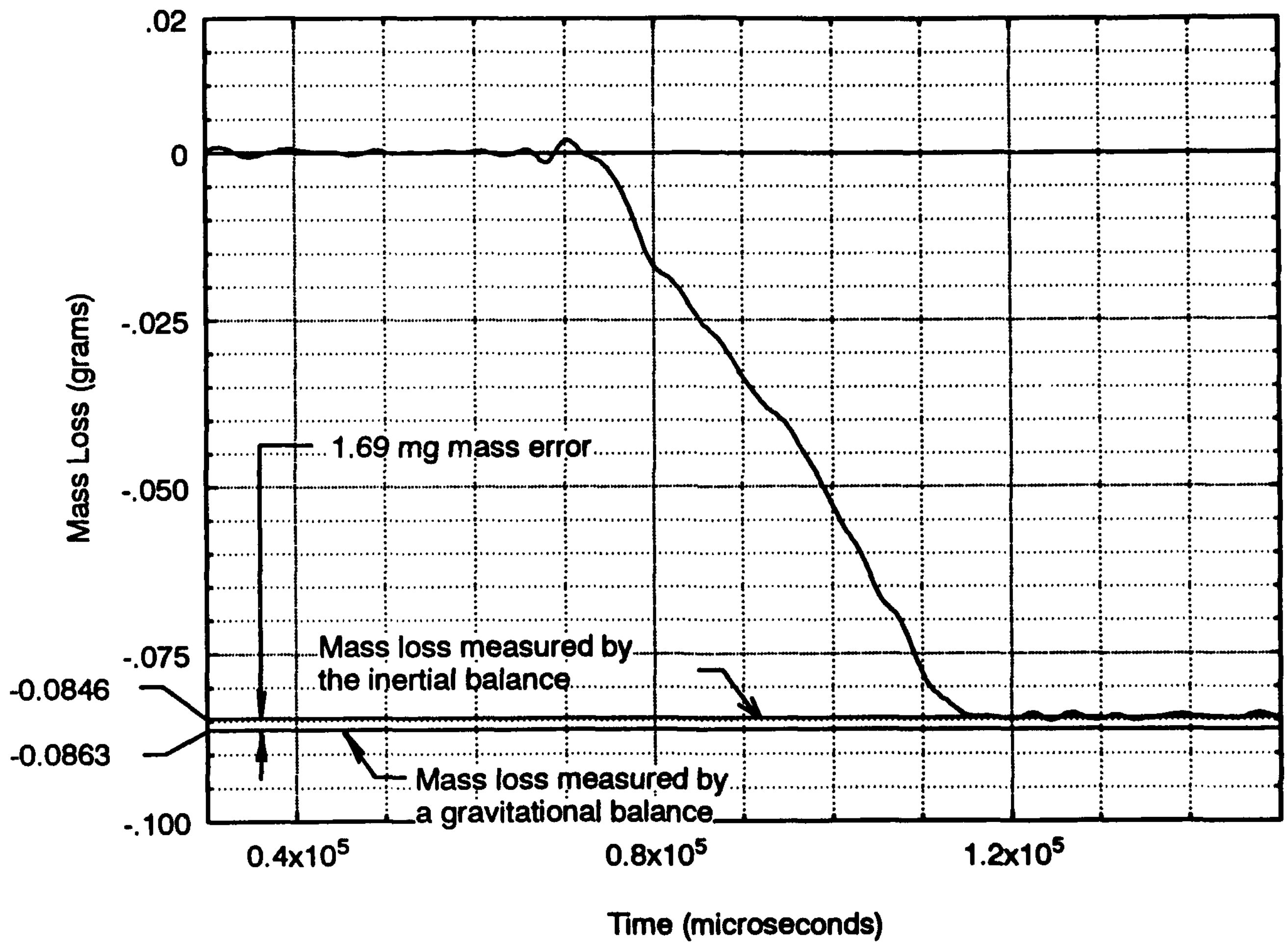


Figure 5-3. Coupon ablation test #3 - mass vs time.

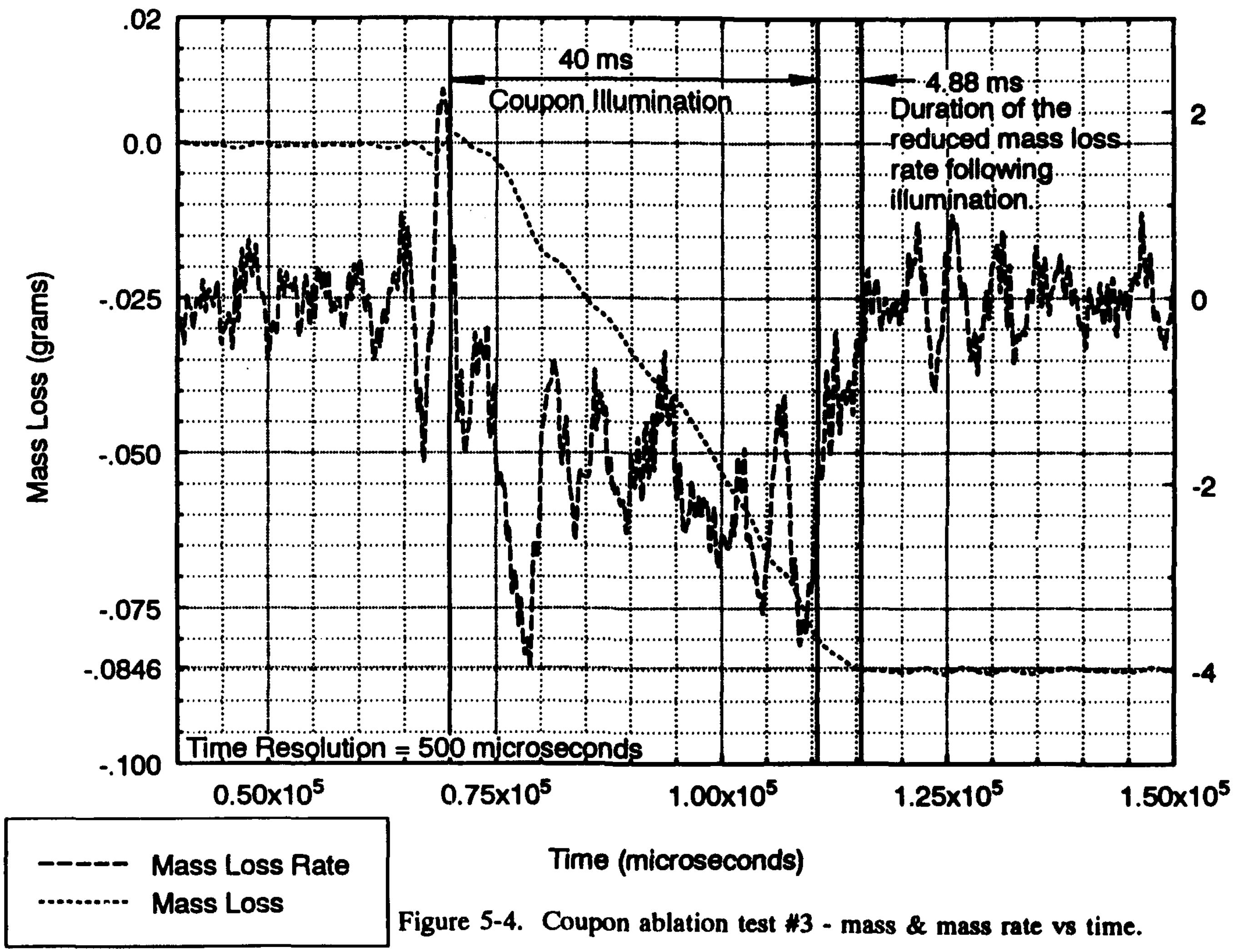


Figure 5-4. Coupon ablation test #3 - mass & mass rate vs time.

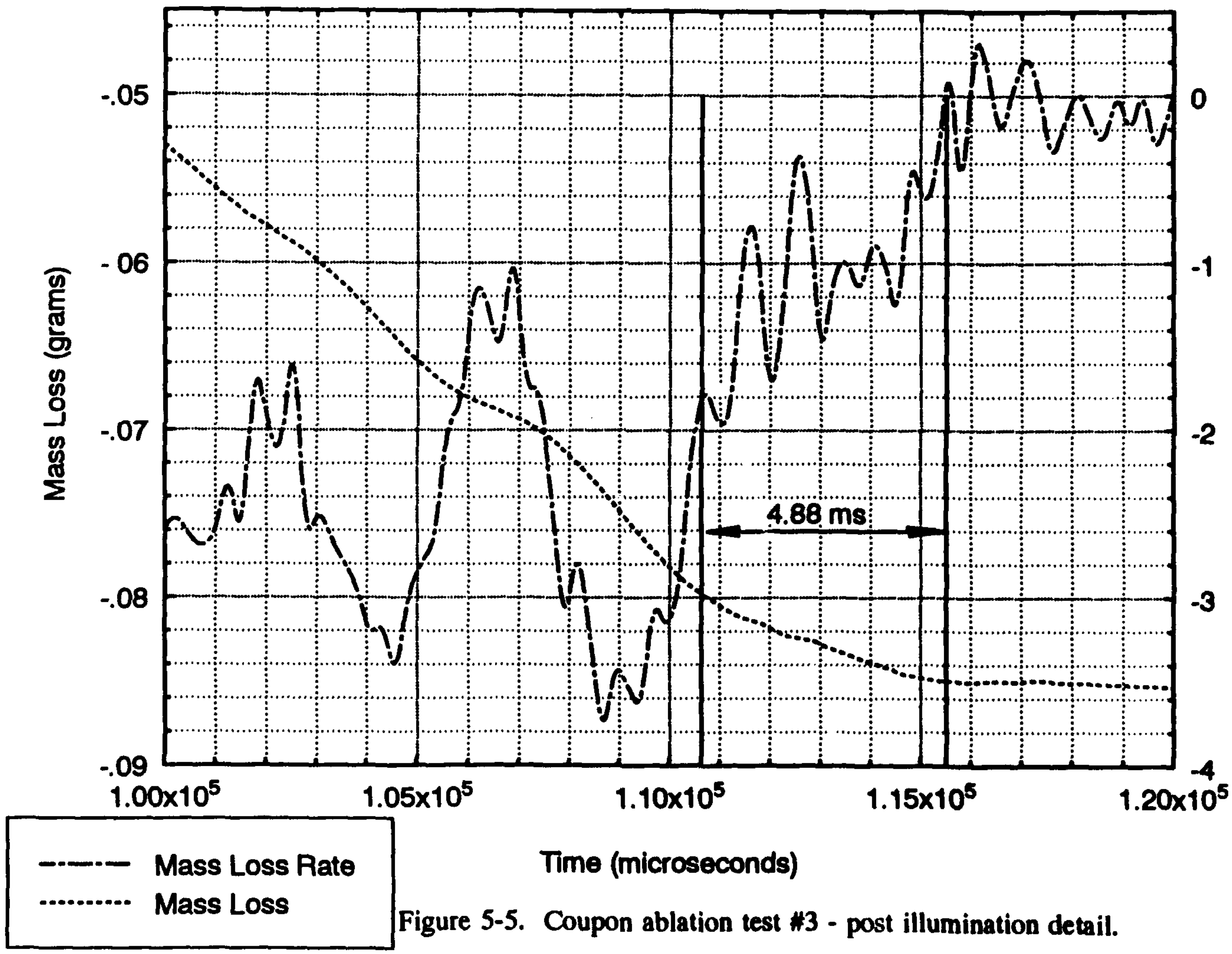
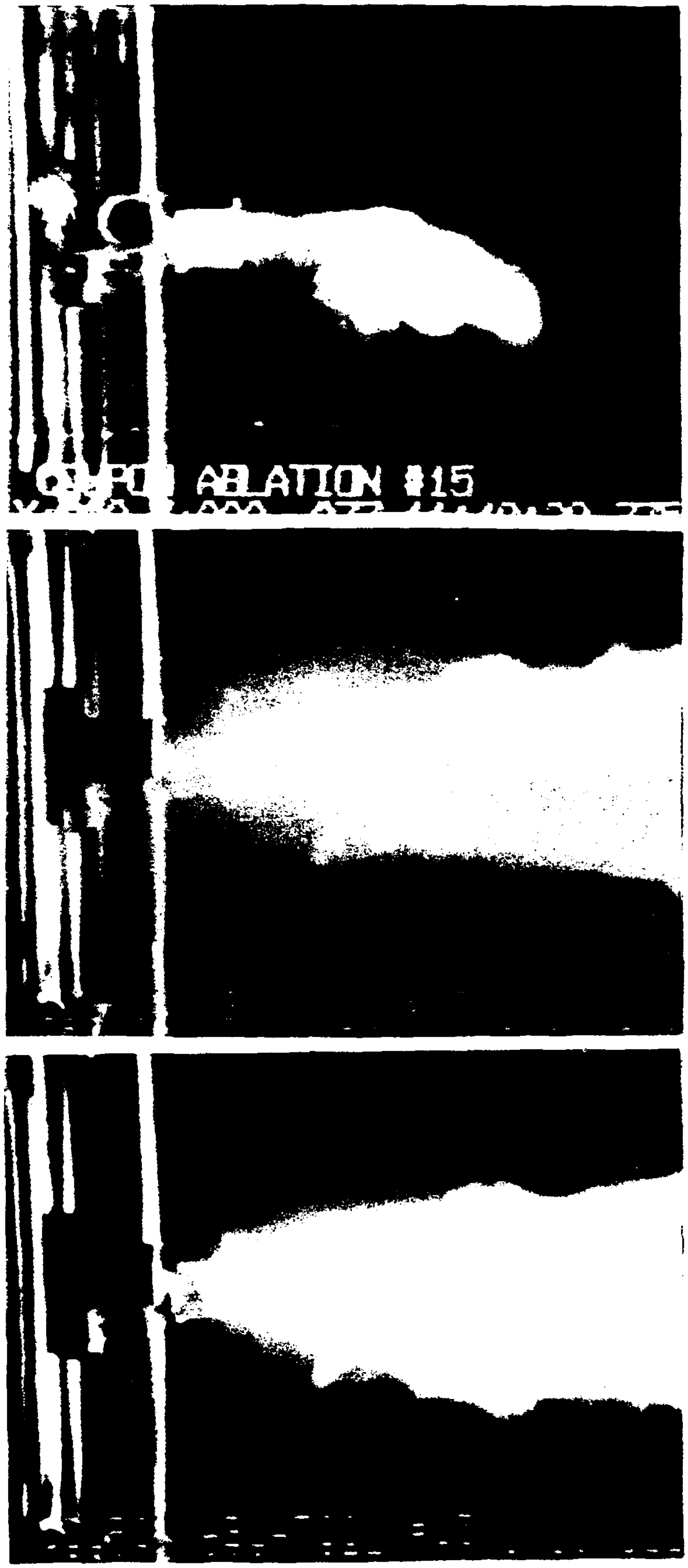


Figure 5-5. Coupon ablation test #3 - post illumination detail.



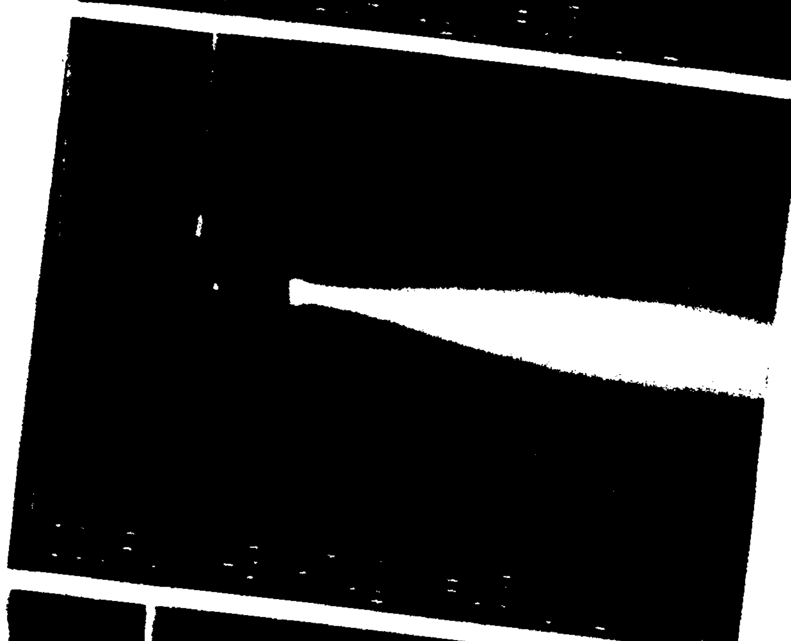
Plume Initiation immediatly following coupon illumination.

Plume during illumination showing nonuniform burning.

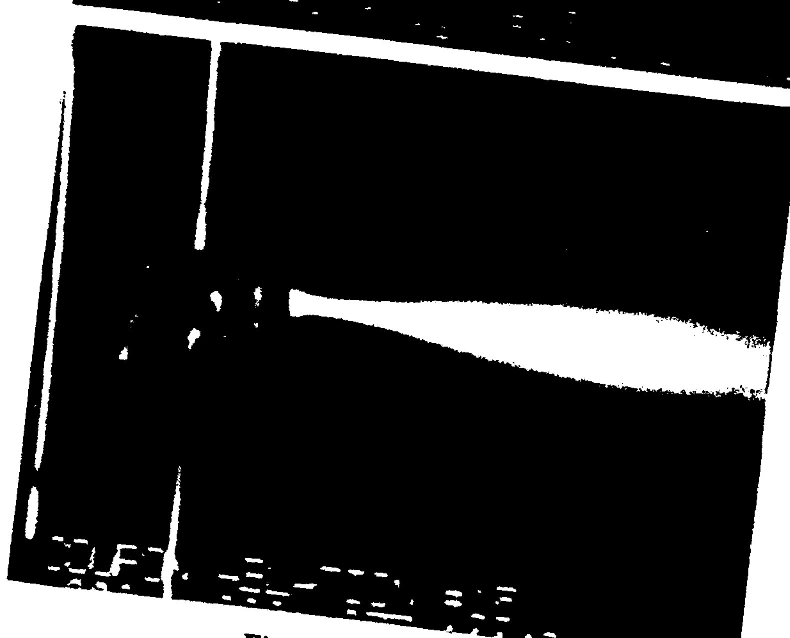
Plume during illumination showing nonuniform burning.

Figure 5-6. Plume sequence.

Plume following illumination showing a decreased more uniform burn.



Plume decreasing as surface cools.



Plume decreasing as surface cools.

Figure 5-6. Plume sequence. (continued)

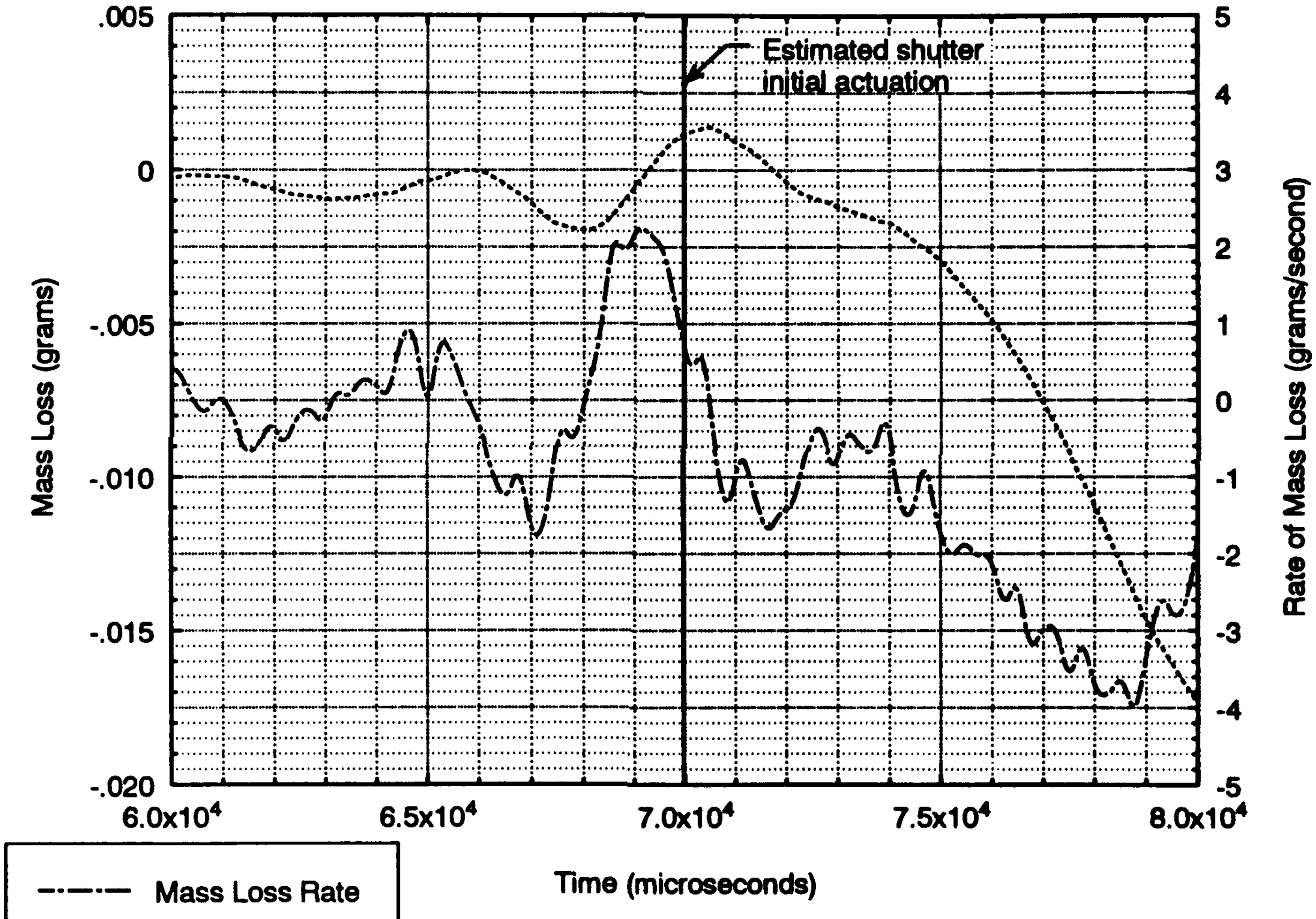


Figure 5-7. Coupon ablation test #3 - initial illumination detail.

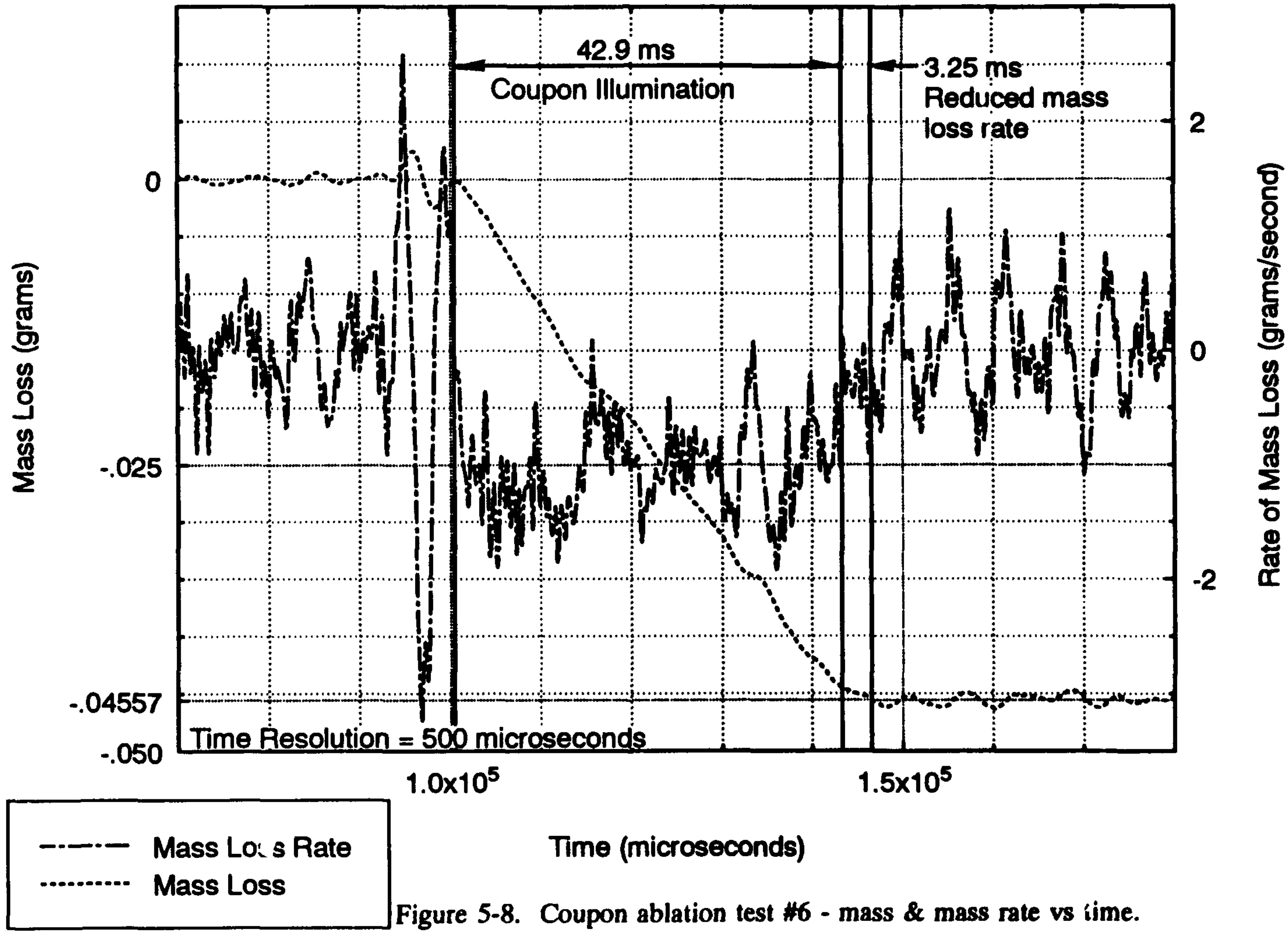


Figure 5-8. Coupon ablation test #6 - mass & mass rate vs time.

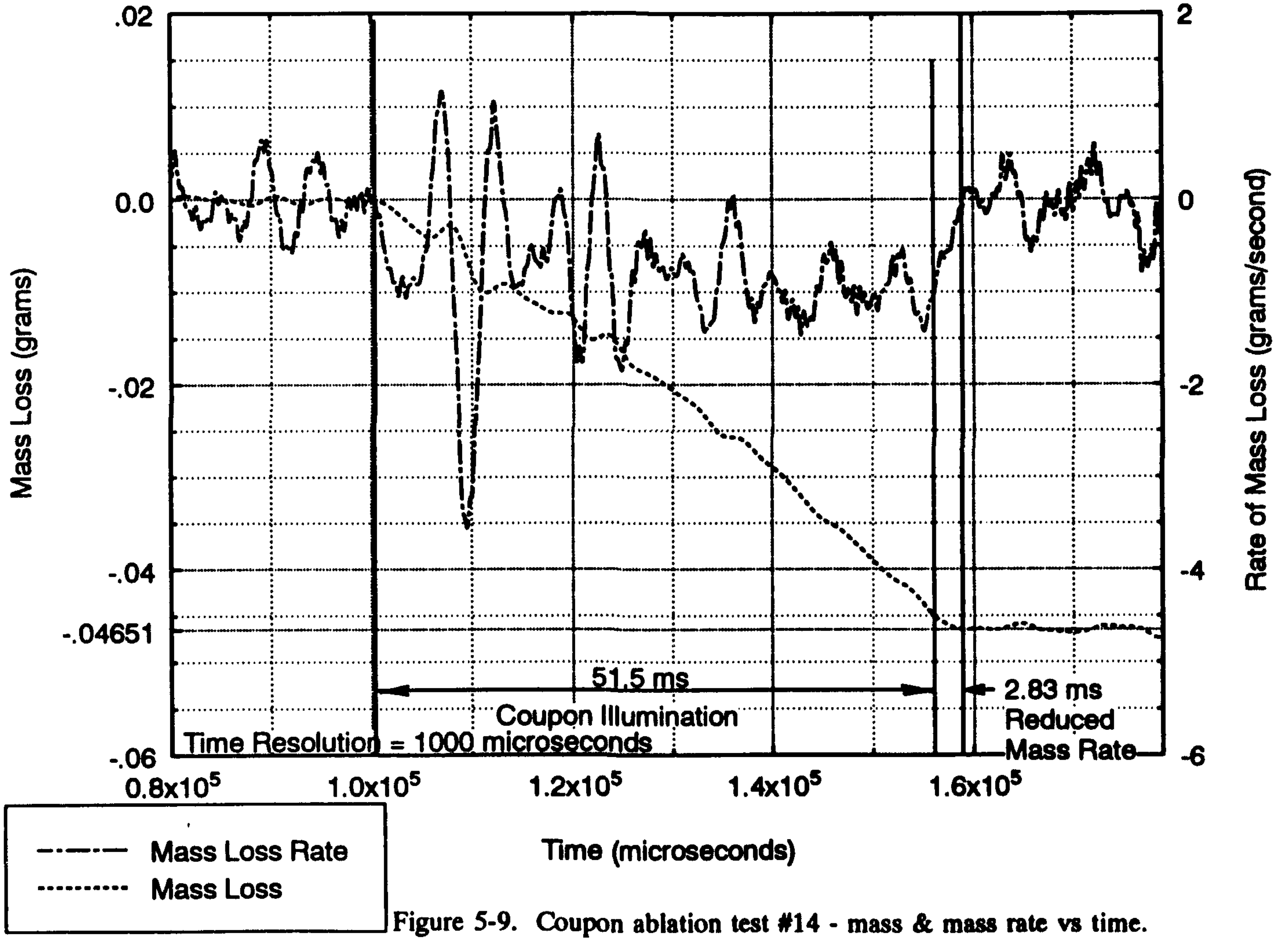


Figure 5-9. Coupon ablation test #14 - mass & mass rate vs time.

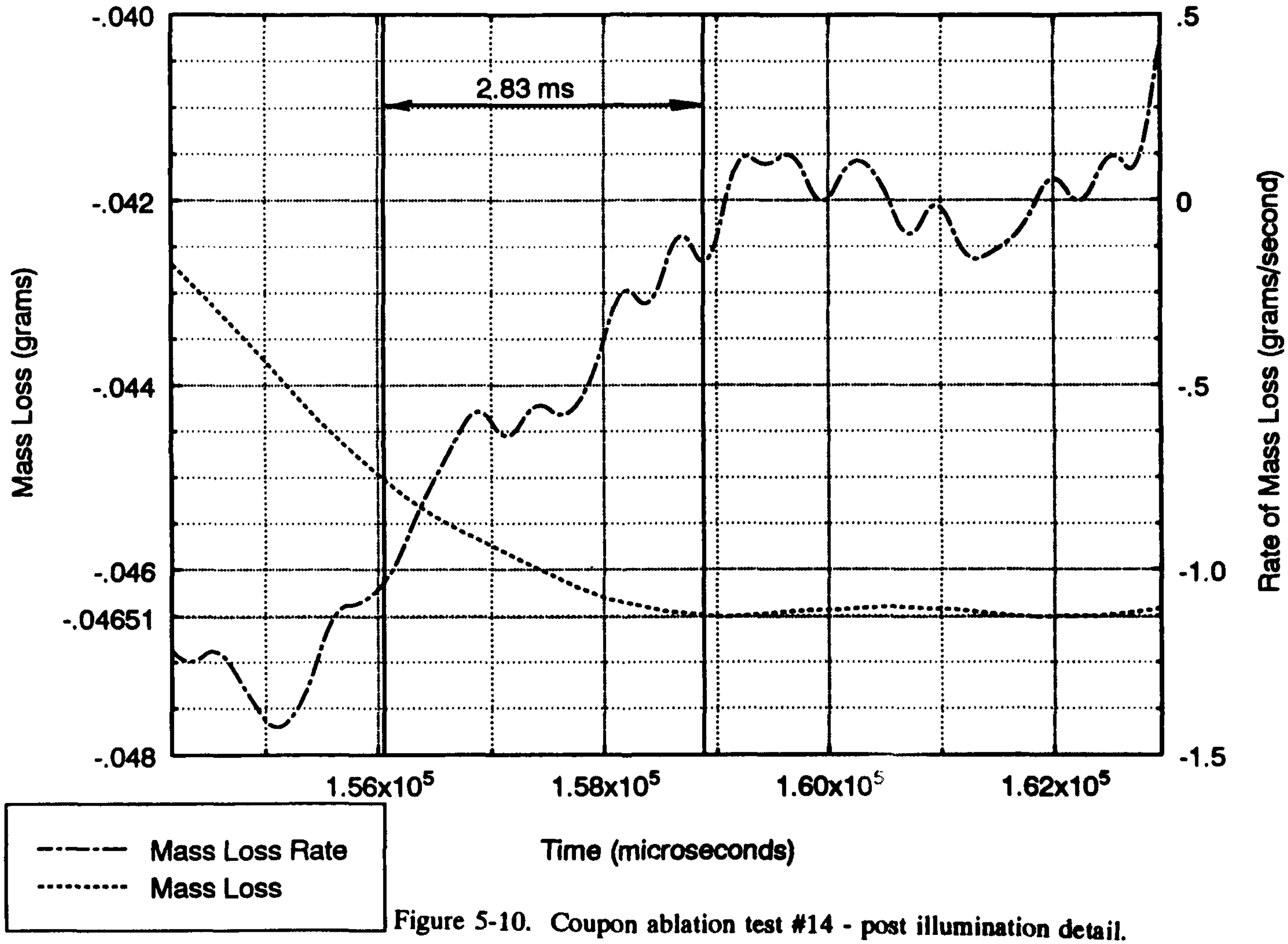


Figure 5-10. Coupon ablation test #14 - post illumination detail.

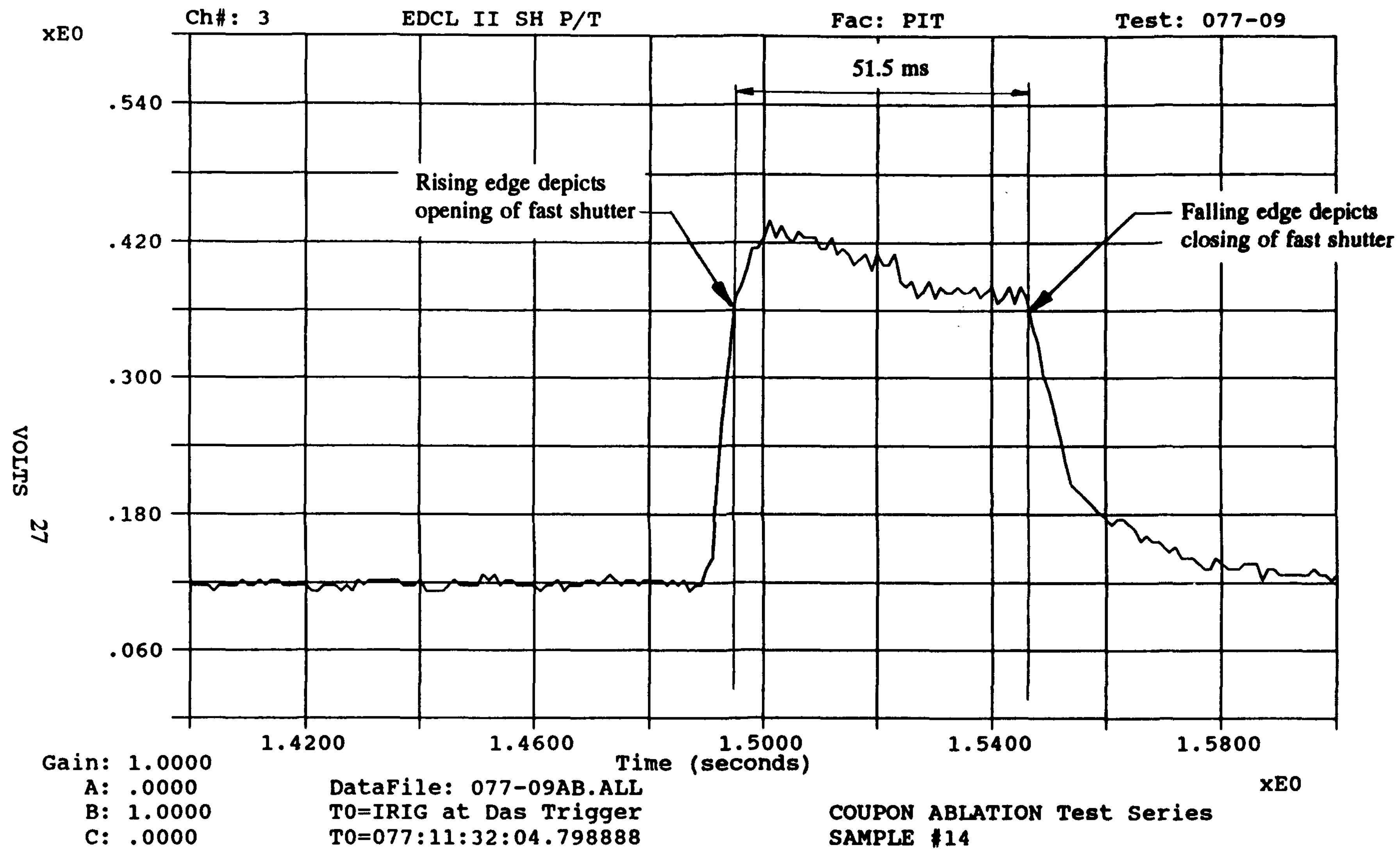


Figure 5-11. Coupon ablation test #14 - fast shutter response.

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